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Original article

Consolidation of weak lime mortars by means of saturated solution of calcium hydroxide or barium hydroxide

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ABSTRACT

This paper presents research results on the effects of repeated treatments with saturated solutions of calcium hydroxide (lime water) or barium hydroxide (barium water) on consolidating a friable lime mortar. The influence of lime or barium water treatment on various mainly mechanical characteristics of consolidated lime mortar was studied in detail by means of tests on non-standard specimens fabricated from a poor mortar of 1:9 vol. lime-to-sand ratio. The traditional lime water technology and barium hydroxide treatment were further compared with distilled water and lime water with added metakaolin. Lime water treatment of a specific lime mortar was shown to be effective after a sufficiently large number of applications (160 saturations) into a weak lime mortar. No consolidating effect of distilled water on the compressive strength of the tested mortar with a low lime content (1:9) was observed. The mechanical characteristics of the tested mortar were not improved by treatment with lime water with added metakaolin. Barium water treatment significantly increased mainly the tensile strength of the tested lime mortar.

1. Research aims

Discussions on the use of a solution of calcium hydroxide in water (often referred to as "lime water") for consolidating weak inorganic porous materials have been going on for decades. In the Czech Republic, multiple applications of lime water have frequently been prescribed by the central national conservation office as the only acceptable consolidation treatment for lime renders. Such massive application of lime water as a consolidation agent for conserving historic rendered façades has raised much discussion, and has aroused the resistance of some regional authorities and practicing restorers, leading to the involvement of our team in laboratory research on this contentious issue. The authors of this paper take a neutral position, and their research aims to offer an objective evaluation of the influence of adding lime water to friable mortar, and to ascertain the degree of consolidation. The consolidating effects not only of lime water but also of multiple applications of some other treatments were investigated: distilled water, lime water blended with metakaolin, and barium water (a barium hydroxide saturated solution in water). In this study, barium hydroxide was considered as an alternative "traditional" consolidant to calcium hydroxide, and potentially more effective, because it is much more soluble in water than calcium hydroxide. With respect to the distilled water, its effects were investigated with reference to the type of mortar and the shape of the specimens. The lime water with added metakaolin was tested in accordance with recently published research results.

2. Introduction

Until the recent publication by the authors of this paper [1], there was a lack of experimentally supported publications and detailed information about the effects of lime water treatment on weak lime mortars. Some papers presented only marginal data [2] or the results attained under certain limited conditions may be too broadly interpreted [3], and may be arbitrarily extrapolated into conditions where no knowledge is available, and thus no justification or evidence exists [4]. Though the number of relevant articles is quite small, a detailed literature review is beyond the scope of this paper. Only the most relevant experimental studies are mentioned, leaving aside reviews [5], theoretical works analysing, for example, very important questions of binding mechanisms [6,7], and also papers illustrating confusions in terminology (lime water against lime wash) [8] or presenting discussions and arguments against the application of lime water for consolidating mortar and stone [9].

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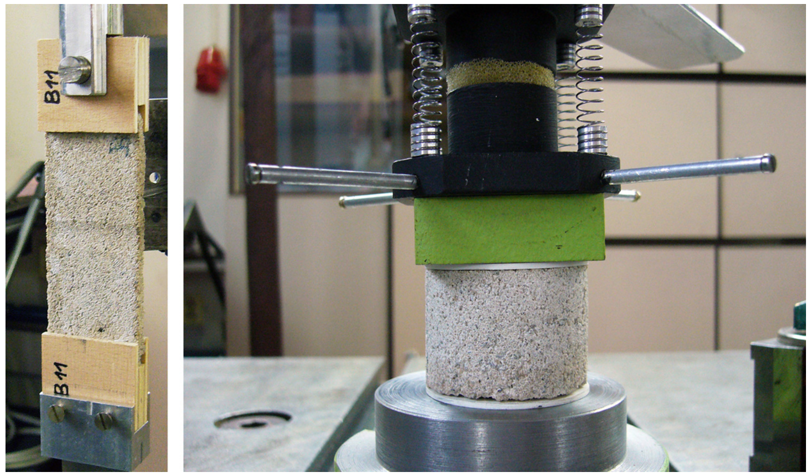

Fig. 1. Testing specimens – tubes for compressive and thin plates for tensile tests.

The effect of lime water applied *in situ* for restoring wall paintings on lime mortar rendering has been investigated by I. Brajer and N. Kalsbeek [10]. These researchers systematically tested lime water treatments from the point of view of the application procedure, the number of applications (20–70 cycles), dosage and maturation. They concluded that continuous "wet" applications bring about a consolidation effect, unlike applications with "drying" breaks, which do not consolidate the wall painting. However, the observed consolidation tended to concern fixation of a released surface paint layer, for which lime water was recommended in some older literature [11]. (It is interesting to note that the so-called "traditional" lime water was not included by Friedrich Rathgen in the list of consolidation techniques that he compiled in 1898. In former Czechoslovakia, F. Petr added lime water to the list of recommended treatments in 1953, without any reference [12]). I. Brajer and N. Kalsbeek did not carry out any objective measurements of mechanical characteristics in their study.

In the field of measuring the mechanical characteristics important results were published by C. Price [13] and his team [14]. Although this work concerns limestone restoration, it has helped considerably in the presented study. C. Price applied lime water in 40 cycles on stone and also on crushed limestone sand. He found a very small increase in the amount of calcite in the material, no observable change in the mechanical characteristics, and no consolidation effect on the crushed material.

Lime water effects and the use of metakaolin as an additive in lime water were studied by M. Tavares, R. Veiga and A. Fragata [15]. They recommended the use of lime water and lime water with metakaolin for consolidating old rendering with low cohesion on the basis of laboratory and in situ tests results, and concluded that the tested consolidants increase the mechanical resistance of the superficial layers.

Notwithstanding the research referred to above, there has been a considerable lack of knowledge concerning the method of lime water treatment of renders. A thorough experimental programme was therefore carried out, aimed at revealing the fundamental behaviour of weak lime mortars when subjected to multiple saturations and evaporation of distilled water, a saturated solution of calcium hydroxide in water ("lime water"), lime water with added metakaolin, and saturated solution of barium hydroxide.

3. Experimental

3.1. Lime mortar test specimens

On the basis of a literature survey indicating very slight effects of multiply wetted historic mortars or stone with lime water, as regards to both penetration depth and strengthening, the authors designed and prepared specific test specimens in the form of short tubes for compressive tests and plates for tensile tests (Fig. 1 and Table 1). The specimens were made of lime mortar prepared in laboratory from powdered lime hydrate and river sand. The white air lime hydrate (CL90) Čertovy schody, Czech Republic, of a great purity (98.98% of CaO + MgO) was used. The most frequent particle diameter found in lime was 15 μm and 90% of particles were smaller than 38 μm (the particle size distribution was measured using a Laser analyser CILAS 920). The specific surface area of used lime was 16.5 m^2/g (by means of gas adsorption, BET method, using the device Micromeritics ASAP 2020).

As the aggregate of the mortar, a quartz sand was used (sand quarry Borek, Czech Republic). Mineralogical composition of the sand was determined by means of optical microscopy (thin section of the sand was investigated by the polarizing microscope Zeiss NU2) and XRD analysis (Bruker D8 Advance system with Cu-anode ($\lambda_{K\alpha}$ = 0.15418 nm) and variable divergent apertures at convention Bragg-Brentano para-focus Θ–Θ reflective geometry, step 0.02°2 Θ, step time 188s). The sand consisted mainly of quartz, but particles of quartzite, marlstone, granitic rocks, K-feldspar and plagioclase were also determined using petrographic microscope. XRD analysis identified quartz, feldspars, illite, and/or muscovite, and chlorite. Particles of the sand Borek were sorted in grain size fractions by means of sieving before preparing the laboratory mortar. The grain size distribution of the aggregate for mortar specimens, Table 2, was designed so that it reproduced the grading of the historic render aggregate. For this purpose, the historic lime render with quartz aggregate was sampled from a medieval castle and the sample of 200 g was dissolved by the acid dissolution. The

Table 1
Specimens parameters.

Specimen shape	Length (cm)	Width (cm)	Thickness (cm)	Volume (cm^3)	Treated surface (cm^2)	Porosity (MIP) (%)
Tube (compression test)	3	4	0.55	17.3	37.7	27
Plate (tension test)	10	4	0.5	20	40	

Table 2
Grain size distribution of the lime mortar sand (sieving analysis).

Size (mm)	< 0.063	0.063–0.125	0.125–0.25	0.25–0.5	0.5–1	1–2
% w	0.2	0.7	4.8	36.4	43.6	14.3

aggregate separated from a disintegrated mortar by filtration was dried and sieved to obtain the grading curve of the mortar aggregate. In accordance with the grain size distribution of the historic render, the various size fractions of the sand Borek were mixed and used for preparation of the model laboratory mortar.

The quartz sand and the commercial air lime hydrate CL 90 in a ratio of 1:9 by volume (2.5 kg of the dry sand mixture, 0.1 kg of the lime hydrate and 0.25 kg of water by weight) were mixed in the laboratory to prepare a poor weak lime mortar. First, water was poured into the mixing bowl then the lime hydrate was added and the lime mixture was mixed for 5 minutes in a laboratory mortar mixer. After that the sand was poured into the lime and finely, mortar was mixed 20 minutes. The fresh mortar was stored in a closed plastic bag to prevent the mortar from carbonation.

The specimens were fabricated by casting of the fresh mortar in a stainless steel cast, with no separation treatment of steel walls, and were well compacted. This enabled the specimens to be pushed out from the cast immediately after moulding, and prevented the development of shrinkage defects. The tubular cast shape of specimens for the compressive test increased the surface-to-cross-section area ratio and intensified the measurable compressive strengthening effect. The plates for the tensile tests were provided with wooden (plywood) heads to enable them to be fixed into the special flexible loading grips, ensuring correct alignment without disturbing bending and without eccentricity (Fig. 1). As the study was focused mainly on compressive strength of consolidated mortar, five tubes for compressive strength and one plate for the tensile strength testing were prepared for each consolidation treatment mode (consolidation agent, number of applied cycles, application regime). Mortar specimens were left to harden for six months before consolidation substances were applied. The specimens were cured by slight spraying of distilled water for about one month to support a carbonation process.

All specimens were conditioned before testing in a controlled environment (20 °C, RH 65%). Then, the consolidation agents were applied, and after completion of the consolidation treatment the specimens were left to mature for another 60 days, which was sufficient to allow carbonation of the calcium or barium hydroxides applied into lime mortar specimens by lime water. In both cases (before consolidation substances application and before testing of treatments effects), the level of carbonation was checked by phenolphthalein testing.

The tubes for compressive strength testing were used for peeling tests before their destruction. The other tests (MIP, microscopic examination, water drop absorption, colour parameters) were carried out on samples prepared from the broken test specimens after compressive strength testing because the authors maintain a policy of testing as much as possible identical materials. Therefore, the tests follow a sequence from non-destructive to destructive ones.

3.2. Consolidation of mortar specimens

The following consolidation substances were applied: distilled water, calcium hydroxide saturated solution in water (“lime water”), lime water + metakaolin and barium hydroxide saturated solution in water (“barium water”). The applied consolidation substances are listed in Table 3 together with data relating the consolidation procedure applied on the tube specimens for the compressive test.

Water solutions of calcium hydroxide and barium hydroxide were prepared using chemical products pa (pro analysi) and distilled water. For the lime water solution 2 g of $Ca(OH)_2$ pa were put in 1 L of distilled water; for the barium water solution, 5 g of $Ba(OH)_2{\cdot}8H_2O$ pa were add in 1 L of distilled water and slightly mixed. The solubility of $Ba(OH)_2$ in water made it possible to prepare “barium water” with a higher concentration of barium hydroxide (5% weight) than for the lime water (0.16% weight). The lime water with metakaolin was prepared by mixing of 2 g of calcium hydroxide pro analysi and 2 g of metakaolin in l L of distilled water. Metakaolin used in our study for modification of the lime water was a finely ground burnt claystone, commercial name Mefisto L05 (České lupkové závody Inc., Nové Strašecí, Czech Republic) with relatively high amount of alumina (52.1% SiO_2, 43.4% Al_2O_3). The metakaolin has the particle diameter at 50% of particles equal to 4 μm, 90% of particles size was smaller than 11 μm (Laser analyser CILAS 920). The specific surface area of the metakaolin was determined at 12.7 m^2/g using BET method (gas adsorption device Micromeritics ASAP 2020). The pozzolanic activity of the used metakaolin was determined as the important characteristic of this pozzolanic material using the modified Chapelle test [16,17]. The obtained value was 1002 mg, which represents the amount of $Ca(OH)_2$ fixed by 1 g of metakaolin. The used method is based on the evaluation of reactivity of the metakaolin with calcium oxide in water. The mixture was kept at the temperature of 85 °C for 16 h, after that time the mixture was filtered and the remained CaO content was determined by means of sucrose extraction and titration with HCl solution [18].

Lime water, barium water and lime water with added metakaolin were prepared one week before consolidation treatments and stored in closed glass barrels at laboratory conditions (25 °C, 40% RH) during the all experiment. For consolidation

Table 3
Data related to consolidation treatments applied on mortar tubes.

Tested agent	Active substance	Number of applications per 1 day	Total number of applications	Total amount applied (L/m^2)	Total treating time (days)	Applied agent to specimen mass ratio (g/g)	Applied agent volume to the treated volume ratio (mL/cm^3)
Distilled water	Distilled water	2 (dry)	51	55	25	6.94	11.7
Distilled water	Distilled water	2 (dry)	161	180	80	22.83	38.4
Lime water	$Ca(OH)_2$ pa	2 (dry)	50	52	25	6.38	11.1
Lime water	$Ca(OH)_2$ pa	3 (wet)	58	58	19	7.12	12.2
Lime water	$Ca(OH)_2$ pa	2 (dry)	161	156	80	19.74	34.0
Lime water	$Ca(OH)_2$ pa	3 (wet)	160	155	54	18.72	32.2
Lime water + metakaolin	$Ca(OH)_2$ pa + mefisto L 05	3 (wet)	58	55	19	6.50	11.7
Barium water	$Ba(OH)_2{\cdot}8H_2O$ pa	3 (wet)	58	57	19	6.77	11.8

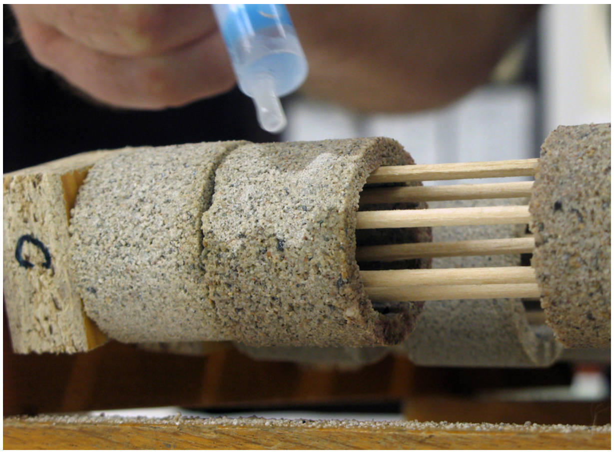

Fig. 2. Impregnation of short tubes, using a syringe.

treatments, a solution above the solid sediment was poured off and used.

Each agent was applied by continually dripping it from a syringe on to tubes fixed in a horizontal position on a rotating shaft (Fig. 2), or lying on supports in a horizontal position (tensile specimens). The mortar specimens were fully saturated during each application of the distilled water or consolidating agent, and we recorded the amount of the agent that was applied. Two treatment schedules were intended for lime water, which was the main subject of the study: 50 resp. 160 series of application of lime water. The lower number of applications (50) represented the level recommended in the older literature [1], whilst the higher number (160) the maximal level of applied cycles followed the recent recommendation how to consolidate historic renders by means of many applied cycles of sprayed lime water into lime renders. The same schedule (50/160 applications) was used for the distilled water treatment to study the difference between effects of lime water and distilled water. In respect to other two studied agents (lime water with metakaolin and barium water), the lower number of applications only was realized with a purpose to compare the obtained effects with lime water applied at the same condition. Particularly in case of barium water, where better effect on mechanical properties of consolidated mortar was expected with individual application, the higher number of applications (160) was considered as needless.

Two different variations of the drying time interval between two following saturations were tested for the lime water: first, 2 applications per day were performed, and the mortar tubes were allowed to dry completely before the following saturation (wet to dry alternative); and second, 3 applications per day were performed, and the new dose of the lime or distilled water was applied as soon as the mortar was capable of absorbing it, but before it dried out completely (wet to wet alternative). In case of the lime water with metakaolin and the barium water, only 3 applications per day (wet to wet alternative) were performed.

However, the intended number of application has not been managed in the experimental work precisely and really applied cycles of consolidating agents have slightly varied from the original schedule (58 cycles instead of 50 were realized for the wet to wet alternatives and 161 instead of 160 cycles for the wet to dry alternative). Also for the treatment of plates intended for the tensile strength test, the number of applications was modified slightly. The purpose to study the influence of lower and higher repeated applications number for lime and distilled water was kept.

3.3. Mechanical characteristics

All mechanical tests were carried out on an electromechanical loading frame TESTATRON with the maximum loading capacity of 100 kN at laboratory conditions (RH 65%, T 20 °C), load cell Lucas 2 kN (typically for tension tests) or 10 kN (typically for compression tests) and crosshead velocity movement of 0,45 mm × min^{-1}. The short mortar tubes were loaded along the tube axis in compression (Fig. 1). The attained compressive strengths were checked against those measured on a set of rectangular specimens. The average compressive strength determined from the untreated tubular reference specimens was 0,260 MPa, and the average compressive strength measured on the rectangular specimens was 0,549 MPa, which corresponds after a low slenderness ratio correction [19] to the cube compressive strength of 0,365 MPa. In fact, such a relation is not necessary for a comparative study of this type, because the effect of the individual agents was tested on identical specimens and the overall behaviour was compared. However, it follows from the results that the tubular specimens provide lower compressive strength – approximately 50% of the values measured on the

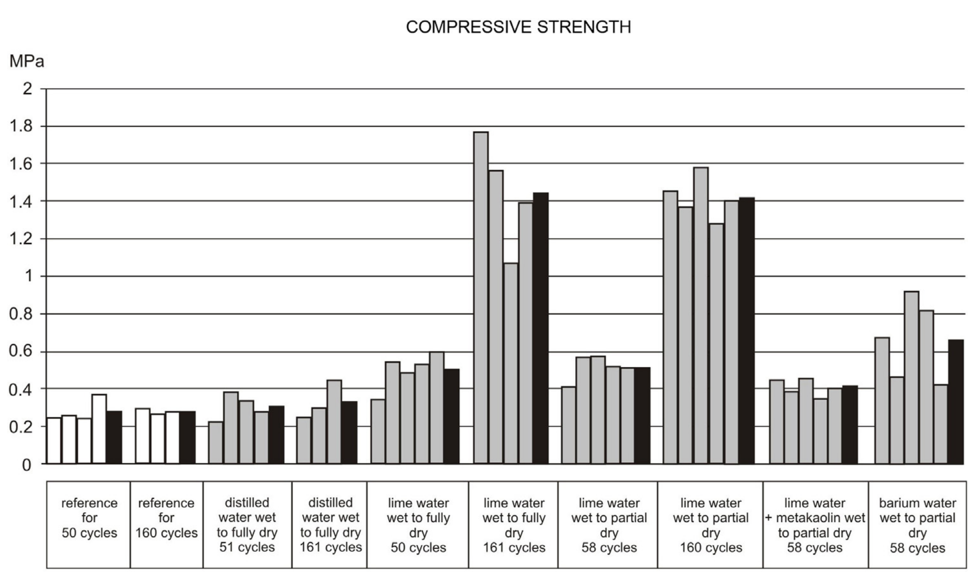

Fig. 3. Results of compressive tests on tubes consolidated by various agents.

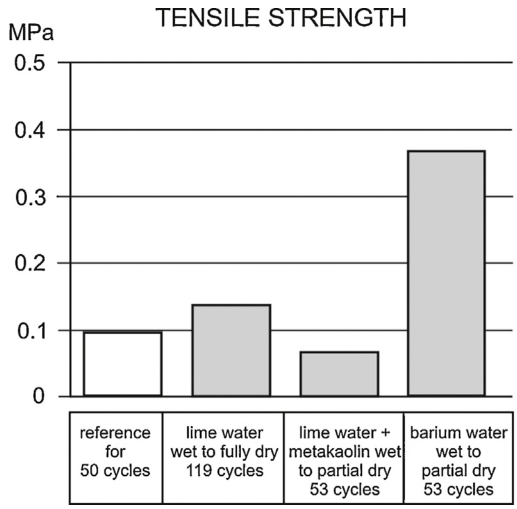

Fig. 4. Results of tensile tests on thin plates consolidated by various agents.

rectangular 40 × 40 × 27 mm (non-standard) specimens, and that the poor mortar that was used really is weaker than usual historic masonry lime mortars, e.g. [20]. Of course, this "weak" mortar was very well compacted and integrated, and was not intended to model the typical sand-like disintegration of degraded mortars. In spite of the fairly good cohesion of the tested mortar, a quite extensive loss of surface material during treatment was observed, even though the treatment was very delicate. The same effect is typical for in situ applications, when the ancient mortar is sprayed with lime water (see further). The average compressive strength was calculated from tests on five specimens.

Tensile strength was tested on a small sample of specimens (from one to two), and the values given here should be considered only as informative. The test arrangement is shown in Fig. 1.

The results of mechanical tests are presented in Figs. 3 and 4. In the Fig. 3, all tested specimens are displayed (light colour fill) with the average values (dark colour fill). Mostly five specimens were tested, in few cases, the fragile model mortar did not sustain treatment and movement and was damaged before testing. Then, only four specimens were tested. It is seen in the Fig. 3 that the scatter of results was mostly very narrow.

The amount of new calcite after lime water treatment is sufficient to make a slight improvement in the shear cohesion characteristics, and thus also in the surface cohesion characteristics.

Fig. 4 shows that barium water treatment is about three times more efficient than lime water treatment, when the efficiency is measured by the change in the tensile strength, which corresponds to a higher concentration of the active compound (barium hydroxide) in the solution. The greater density of the newly crystallized tissue is apparent in the figures mentioned above. Both agents penetrate easily into such a porous mortar.

Fifty cycles of lime water with drying (two saturations per one day) and also 58 cycles of lime water applied more often (three saturations per one day), led to an increase in the compressive strength of the thin-walled tubes. However, this gain was very small. The results further show that there is no apparent difference in compressive strength between lime water application with total drying and with partial drying. There is a considerable increase in the compressive strength of a poor lime mortar after 160 cycles (in the case of two saturations per day, and also in the case of three saturations per day).

The combination of lime water with metakaolin did not provide any benefit. No detectable improvement of the lime water due to modification with metakaolin was observed. This indicates that the products of the pozzolanic reaction of metakaolin and calcium hydroxide in lime water were not water-soluble, did not penetrate throughout the mortar, and therefore did not improve its compressive strength. The lime present in the lime–metakaolin suspension was partially consumed due to a pozzolanic reaction with metakaolin, and the following consolidation treatment of the mortar with lime–metakaolin water was less effective than simple lime water treatment.

Better results were achieved with barium water, although a direct comparison in terms of effectiveness of the active agent is biased by the higher concentration of $Ba(OH)_2$. Samples undergoing the same number of treatments (58) show a higher compressive strength when barium water was employed with respect to lime water. Although the observed improvement in mechanical properties is not as large as might have been expected considering the higher concentration of $Ba(OH)_2$ in the saturated solution, this allowed for a lower number of treatment and lower amount of water introduced into mortar to achieve the same result. As far as the tensile strength is considered, barium water granted much better results. In fact, the strength after consolidation was more than three times higher than that of the untreated reference mortar.

Distilled water did not show any consolidating effect on the tested mortar with a low lime content. In this case, only compressive strengths were measured, and the difference from the reference specimens was insignificant. Probably the repeated dissolution and precipitation of the calcium carbonate presented in the treated mortar with a low content of lime, was not accompanied by a significant redistribution within the volume of the specimen and no relevant microstructural changes occurred.

3.4. Peeling tests results

The peeling method involves peeling off the surface material by sticking some scotch tape to the surface and then removing it [21]. The peeling test method is very sensitive to surface roughness, which leads to difficulties when testing mortars. Though the results correlate with the mechanical characteristics of the material, the relationship between the released material and strength has not been appropriately explained. However, this test can be used for a

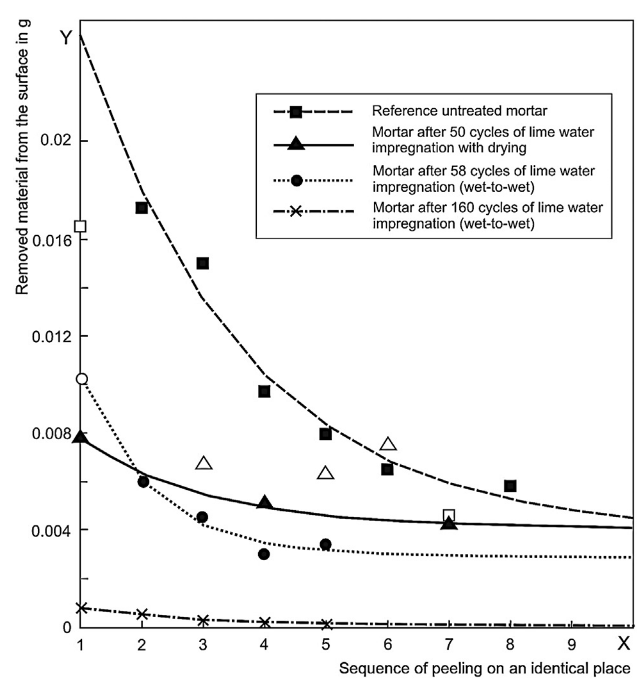

Fig. 5. Peeling test on tubes after mature consolidation.

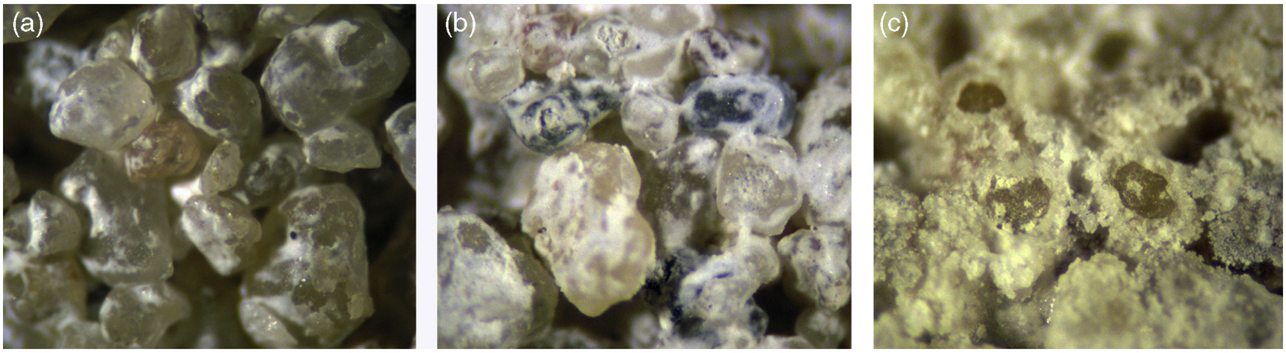

Fig. 6. Macroscopic structure of the untreated weak lime mortar substrate. a (left): reference; b (central): 161 lime water saturations; c (right): 58 barium water saturations.

very rough check on the consolidation effect. In the authors' experience, it is only necessary to keep to the recommended procedure, which consists of repeating the test on the same surface area several times (optimally 10 times) before applying the treatment, and doing the same again after the treatment. The recommended and correct procedure has been suggested in [22]. Fig. 5 shows that after 50 cycles of treatment with lime water no significant effect was observed. After 160 cycles, a positive effect is apparent. For the measurement, a two-sided tape *fix o moll*®, 40 mm in width was used.

3.5. Change in structure

Solutions with higher amount of the active agent deliver a much greater amount of the resulting salt into the mortar, and help to form a stronger binding structure. Fig. 6 illustrates the basic differences between untreated mortar and mortars treated with lime water and barium water, respectively, from the macroscopic point of view. (Pictures taken by an optical microscope SZP 11-TH, magnification 10 ×).

At microscopic scale, Fig. 7 shows a comparison on an identical scale of SEM (MIRA II LMU by Tescan Corporation) SE images of typical $CaCO_3$ and $BaCO_3$ formation after various treatments. It seems that calcium carbonate has grown in the columnar form in the untreated mortar, together with tabular crystals. The matrix is quite thin, with weak bridges. After 161 cycles of lime water treatment in the mode of full drying between subsequent applications, the matrix is filled with layers of newly formed calcium carbonate in platelet form. However, the new material forms discontinuous clusters without regular and dense bridging. Fig. 7c clearly illustrates the differences between the consolidating matrices of lime and barium water. Barium water obviously yields a denser and better-connected microstructure, which is reflected in the reported higher efficiency of barium hydroxide consolidation treatment. In fact, in both cases, a nano-sized precipitated phase of carbonates is apparent.

A microscopic study of the cross-sections by means of SEM-BSE, Fig. 8, focused on the distribution of consolidants into the mortar specimen depth profile. External surface of the samples is in the upper part of each SEM-BSE micrograph. Fig. 8a and b show calcium carbonate on the surface layer of the mortar, in the first case for the reference mortar, and in the second case for the mortar treated with 161 cycles of lime water, where a much thicker layer of calcium carbonate is visible. Fig. 8c depicts the dense structure of the barium carbonate on the treated mortar surface.

The SEM-BSE investigation was supplemented by SEM-EDX (EDX by Bruker Corporation) elemental mapping of the cross-sections. SEM-EDX investigations confirmed that the distribution of calcium (calcium carbonate) in the reference mortar and in the treated mortar with distilled water and lime water is rather uniform, and any difference between the different consolidation regimes could not have been distinguished by this method in the magnification that was used. Only the barium water treated specimens presented a significantly higher deposition of Ba (barium carbonate) on the mortar surface layer (Fig. 9).

3.6. Change in porosity

The mercury accessible porosity and the distribution of pore sizes in the reference and consolidated mortars were determined by Mercury intrusion porosimetry, using a AutoPore IV 9500 (Micromeritics Corporation), with pressure range of 0,005–413 MPa. The mercury parameters were set to values of 485 erg/cm^2 for the surface tension of mercury and 130° for the contact angle. Five samples were measured for each consolidation treatment and average values were calculated. It can be concluded from MIP data that all evaluated consolidation treatments slightly reduced the mercury accessible porosity of treated mortars (Table 4). For the lower number of consolidants applications (50–58 cycles), the porosity decreased by about 1%, while for the higher number of application cycles (160) by approximately 3%. No significant difference was found for lime water with metakaolin compared to simple lime

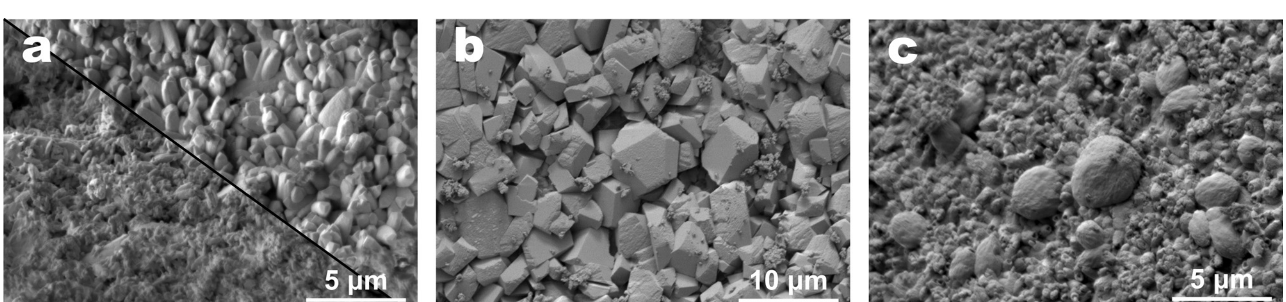

Fig. 7. SEM-SE micrographs of the binder morphology. a (left): reference; b: (central) 161 lime water saturations; c (right): 58 barium water saturations.

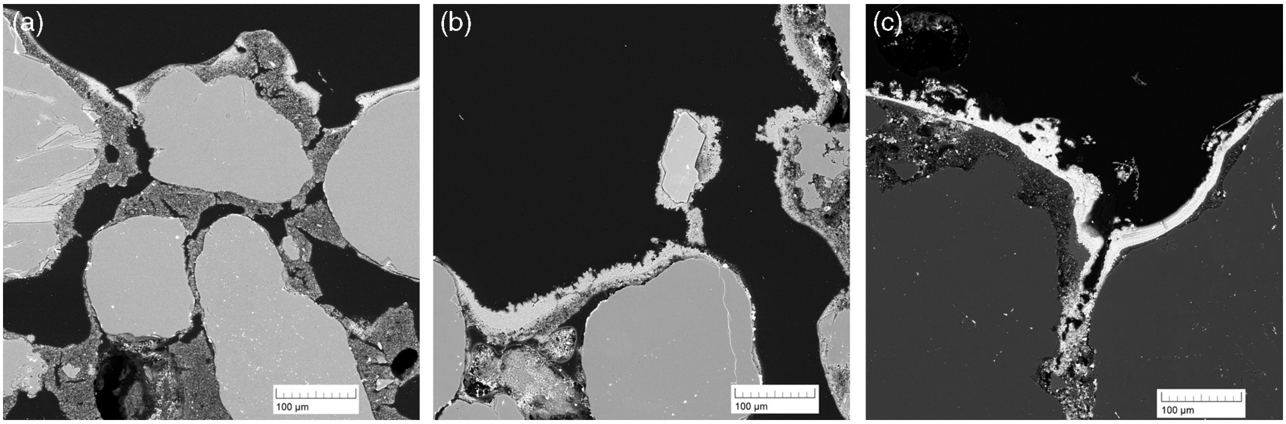

Fig. 8. SEM-BSE micrographs of the structure of the new binder layer (cross-section). a (left): reference; b (central): 161 lime water saturations; c (right): 58 barium water saturations, magnification 700 ×.

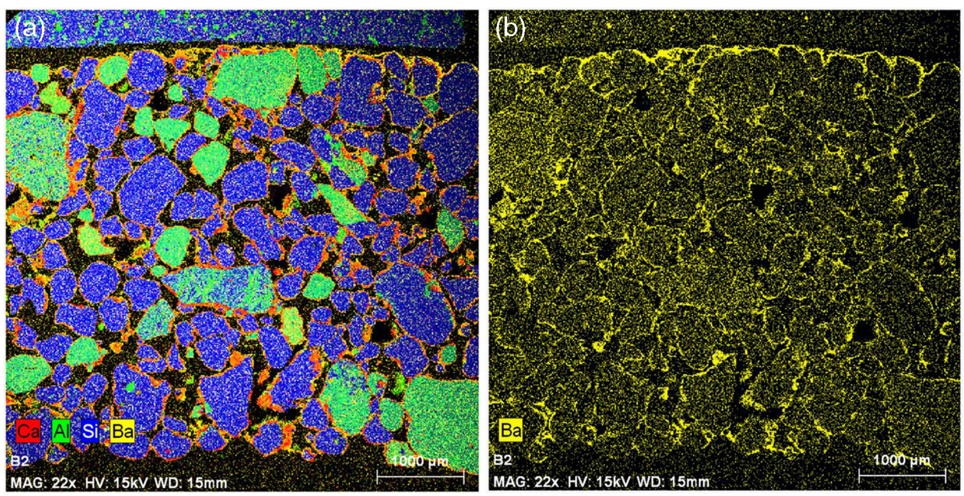

Fig. 9. SEM-BSE micrographs of the lime mortar treated with barium water, magnified 22 ×. a (left): distribution of Ca, Al, Si, Ba elements; b (right): distribution of Ba element.

water. Barium water treatment decreased mortar porosity slightly more than lime water applied at the same condition.

Concerning the mortar pore size distribution, the effects after treatments with lime water, lime water with metakaolin and barium water, are quite small (Fig. 10). The volume of most frequent pores in mortar specimens decreased with increasing number of applied cycles of the lime water. Barium water treatment influenced the pore structure mainly in the range of pores from 0.005–1 μm, creating more uniform pore size distribution. The lime water with metakaolin treatment did not show any significant difference compared to the reference mortar (Fig. 10b).

3.7. Water drop absorption results

The water drop absorption rate is defined as the time taken for a limited amount of water to be absorbed by the surface of the material [23]. A laboratory pipette filled with 0.01 ml of water was used in this experiment. The water drop was applied to the tube mortar specimen surface and the change in the behaviour of the untreated (reference) specimen and the specimen treated with a specific consolidant was evaluated. The time required for total absorption of the water dripped on to surface of the tube specimen from a height of 1 cm was observed by naked eyes and recorded using

Table 4
Porosity by MIP and a change of porosity due to consolidation treatment.

Consolidant	Cycles	Regime	M porosity (% vol.)	M porosity change (% rel.)	Standard deviation (±) [%]	Variation coefficient (%)
Reference	0		27.22		0.36	1.33
Lime water	50	Wet to fully dry	26.21	−3.7	0.42	1.60
Lime water	58	Wet to partial dry	26.66	−2.1	0.78	2.93
Lime water + metakaolin	58	Wet to partial dry	26.47	−2.8	0.45	1.70
Barium water	58	Wet to partial dry	26.14	−4.0	0.51	1.96
Lime water	160	Wet to partial dry	24.48	−10.1	0.68	2.76

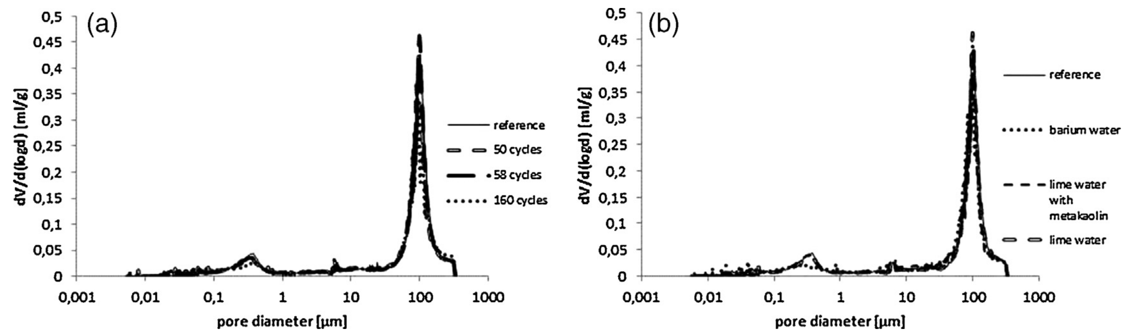

Fig. 10. Pore size distribution of the lime mortar by MIP. a (left): the lime water treatments (various application cycles); b (right): other consolidants treatments (58 application cycles).

Table 5
Water drop absorption rate for individual treatments.

Tested agent, active substance	Total amount of applied consolidant (L/m^2)	Applied agent to specimen mass ratio (g/g)	Applied agent volume to the treated surface ratio (mL/cm^2)	Applied agent volume to the treated volume ratio (mL/cm^3)	Absorption time of water drop (s)
Untreated reference specimen	0				< 1
Distilled water	55	6.94	5.52	11.7	< 1
Distilled water	180	22.83	18.17	38.4	< 1
Lime water, $Ca(OH)_2$	52	6.38	5.22	11.1	< 1
Lime water, $Ca(OH)_2$	58	7.12	5.84	12.2	< 1
Lime water, $Ca(OH)_2$	156	19.74	16.13	34.0	< 1
Lime water, $Ca(OH)_2$	155	18.72	15.36	32.2	< 1
Lime water + metakaolin	55	6.50	5.54	11.7	< 1
Barium water, $Ba(OH)_2·8H_2O$	57	6.77	5.68	11.8	358

Table 6
$L^*a^*b^*$ coordinates for the investigated specimens.

Tested agent	Number of applications per 1 day	Total number of applications	L^*	a^*	b^*
Untreated sample	0	0	66.8	1.7	7.2
Lime water	3	58	65.5	1.6	7.1
Lime water	3	160	70.1	1.5	5.1
Barium water	3	58	73.8	0.9	3.8

stopwatch. A minimum of five measurements was performed for each consolidation treatment. The mean values of the absorption times for each treatment are reported in Table 5.

For each of the tested water solutions, the change in the absorption rate was only observed for specimens treated with saturated solution of barium hydroxide. Although porosity and pores size of mortar specimens were relatively large, the barium water treatment of 58 cycles caused the significant reduction of water absorption rate. This founding corresponds with SEM-EDX observation, which proved a significantly higher deposition of Ba (barium carbonate) on the specimen surface (Fig. 9).

3.8. Colour change and other application problems

Calcium hydroxide based consolidants require impregnation with a large number of applications or saturations, which may be accompanied by a colour change after carbonation, so-called whitening, white hazing or a blooming effect. Colour change was determined with a spectrometer Avantes AvaSpec 2048 equipped with Avasphere-IRRAD system for collecting reflected light from the surface of samples. Data were collected from the external surface of cylindrical specimens and expressed in compliance with the CIE $L^*a^*b^*$ standard notation. The mean values of three measurements for each point of analysis over three different samples for each treatment and for the untreated sample are listed in Table 6.

Although the sample surface was not flat, irregular and rather in homogeneous (due to the presence of aggregates of different colour), the scattering of the data was relatively small and comprised between ± 0.5.

This allows for drawing the following conclusions: the effect of 58 treatments with lime water did not appreciably change the colour of the sample. However, after 160 treatments, a clear whitening effect can be appreciated. Impregnation with barium water is much more effective in this respect, because lightness is 6 points higher than the untreated samples, and both $\boldsymbol{a^*}$ and $\boldsymbol{b^*}$ coordinates are much lower adding a clear white hue to the original sample. The intensity of such effect can be ascribed to the amount of $Ba(OH)_2$ introduced in the samples, much higher even than that of $Ca(OH)_2$ after 160 treatments.

Laboratory application and also practical application of lime water treatment is characterised by a remarkable loss of loosened material from the mortar or render surface. This amount is influenced by the surface cohesion and the composition of the surface layers. On ancient historic facades, a rather compact and hard crust covers the more disintegrated or even "sandy" subsurface render layer. In these situations, the crust provides natural protection for the original subsurface substance. Repeated wetting with lime water very rapidly degrades the crust layer, opens the systems and makes the crust layer more vulnerable to weathering effects. The achievable consolidation of the sandy layer does not compensate for this negative consequence of the lime water treatment [24].

4. Conclusions

Lime water treatment of a specific lime mortar was shown to be effective after a sufficiently large number of applications (160 saturations) into a weak lime mortar. Some poor mechanical characteristics (compressive strength and surface cohesion) were improved substantially after such a large number of saturations. No consolidating effect of distilled water on the compressive strength of tested mortars with a low lime content (1:9) was observed. The higher concentration of barium hydroxide in its saturated solution resulted in higher compressive strength than in specimens treated in the same mode with lime water, but the increase was not as large as would have been expected according to the concentration of the barium water. The improvement in tensile strength, however, was much better: the strength after consolidation was more than three times higher than the strength of the untreated reference mortar. A microscopic study found differences between the consolidating matrices of lime and barium water–barium water clearly built a denser and better-connected substance. There was no detectable benefit of modifying lime water with metakaolin in terms of the mechanical characteristics of the treated mortar.

All evaluated consolidation treatments slightly reduced porosity of mortar. For the lower number of applications (50–58 cycles), the porosity decreased by 1%, while for the higher number of application cycles (160) by approximately 3%. The presence of pores in the range 0.003–1 μm was detected in mortar treated with barium water. Concerning the distribution of the consolidants into the mortar specimens, a higher deposition of Ba (barium carbonate) on the surface layer of the mortar was detected by SEM-EDX. This finding corresponds with the results of the water absorption test, which showed a reduction in the water absorption rate for this consolidation treatment. On specimens after barium water impregnation, some whitening was slightly observable, while lime water tended to cause less remarkable whitening effect, which was also confirmed by spectrometric measurements.

In studies of the behaviour of consolidants, trials on real objects and also laboratory experiments using model substrates representing a certain type of deteriorated material are an important tool. The task is very complex, and the reader should bear in mind that the tested mortar was cured in the laboratory – there was no surface crust layer or paint present, and there were no soluble salts in the treated material. This is not a common case in most practical situations. The research reported here did not aim to optimize the application of various agents, only to make a comparison under specific conditions. This should be understood in order to avoid misinterpretation of the results.

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